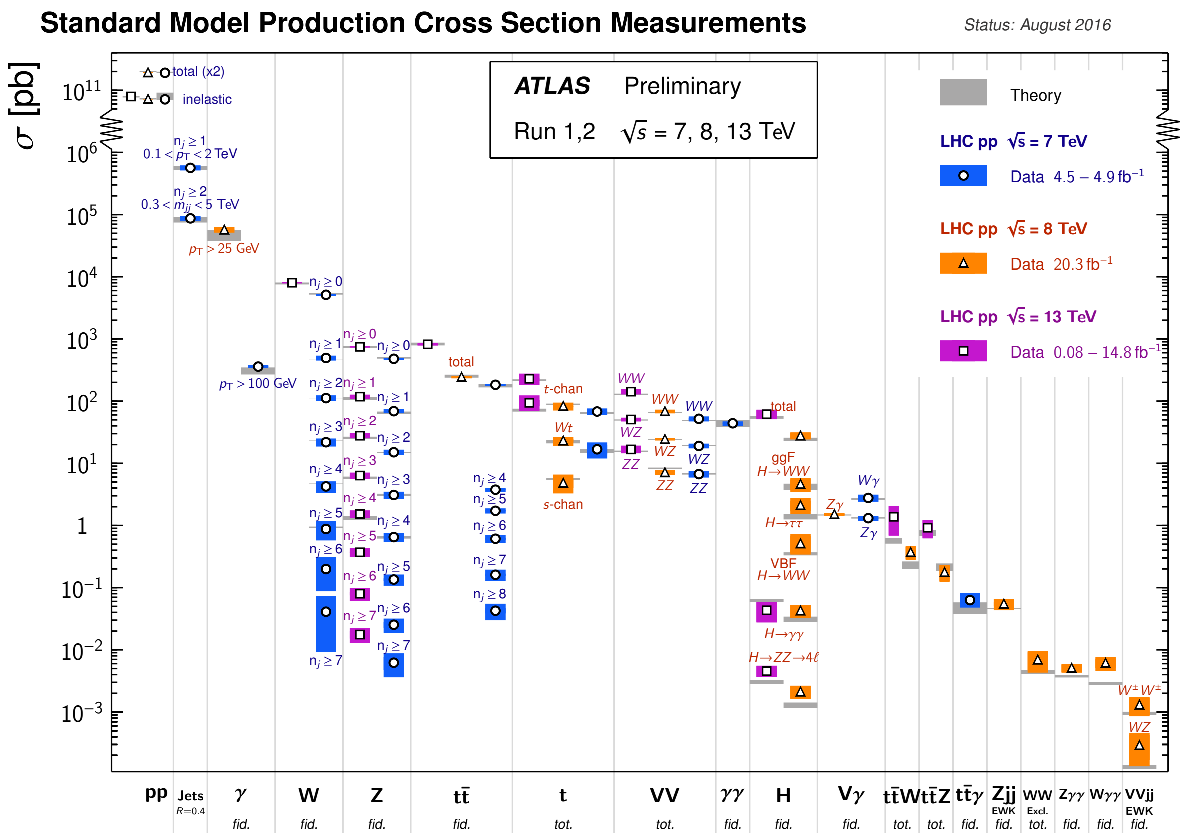
Precision goals for QCD at the high-luminosity LHC

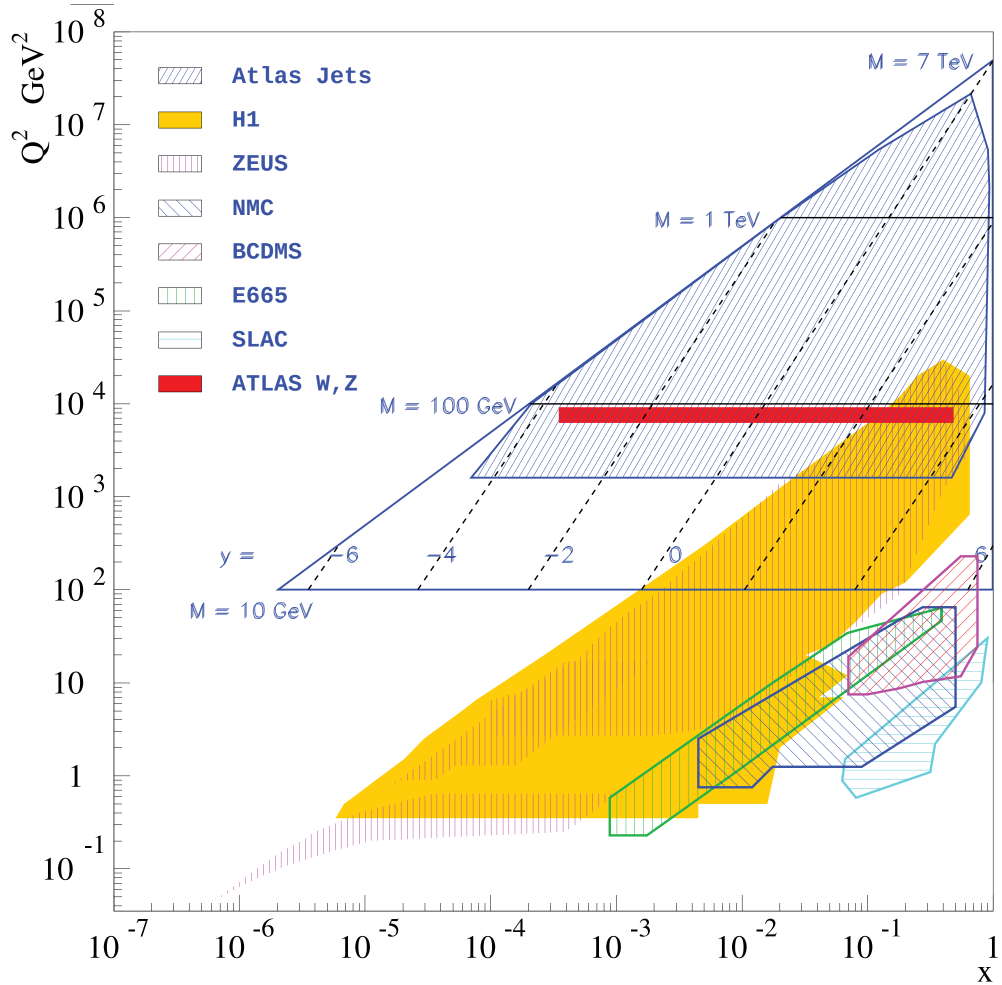
S. Glazov, Philadelphia, 17 Nov 2016

LHC measurements



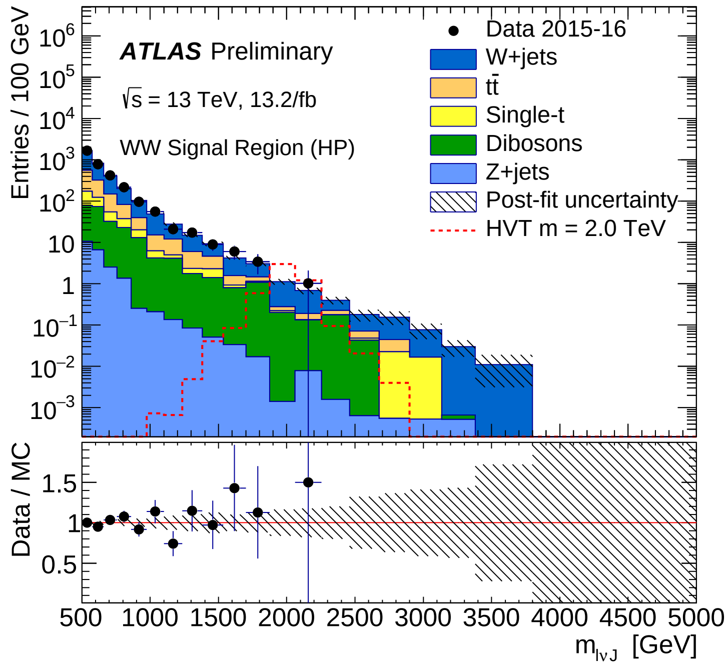
A number of accurate measurements from total cross section to rare electroweak processes. For a few of the processes precision will improve significantly with 300 fb^{-1}, 3 ab^{-1} of data. Stringent tests of SM require accurate theory predictions.

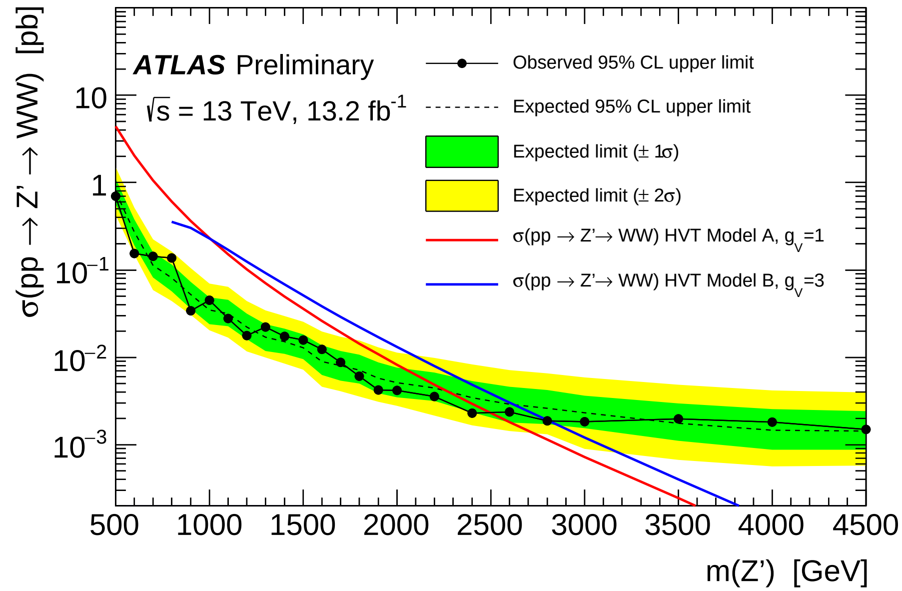
Cross sections at the LHC



The cross sections are given by a convolution of the parton densities and coefficient functions, $\sim x_1 f_1(x_1,\mu)\, x_2 f_2(x_2,\mu)\, \hat{\sigma}(x_1,x_2,\mu)$.
Leading order relation between rapidity y and x_1, x_2: $x_{1,2} = \frac{M_{\ell\ell}}{\sqrt{S}} e^{\pm y_{\ell\ell}}$.

Beyond precision cross sections: boosted jets

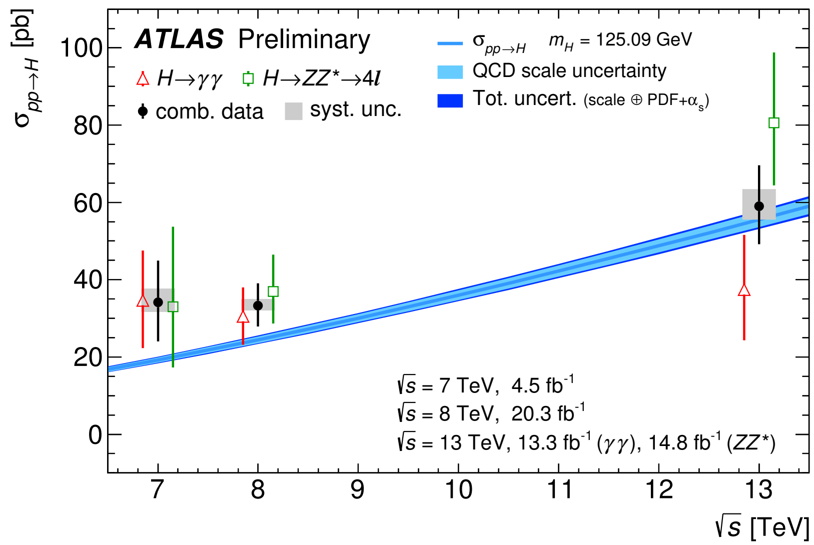


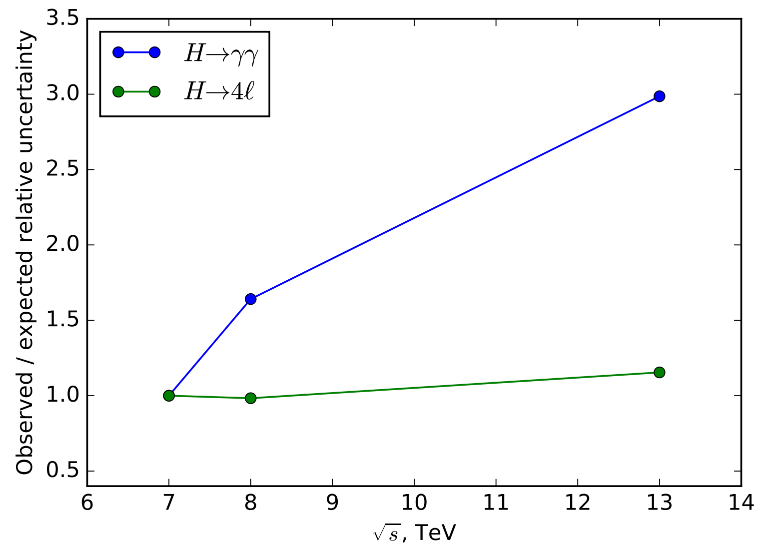


- Larger $\sqrt{s}$ at run-II and FCC increase importance of jet substructure methods.
- Example: ATLAS limits on $Z' \to WW$ using jets with $R = 1$ re-clustered to $R = 0.2$.
- Large background from QCD W+jets. Calibration of jet substructure methods require detailed studies of jet fragmentation.

ATLAS-CONF-2016-062

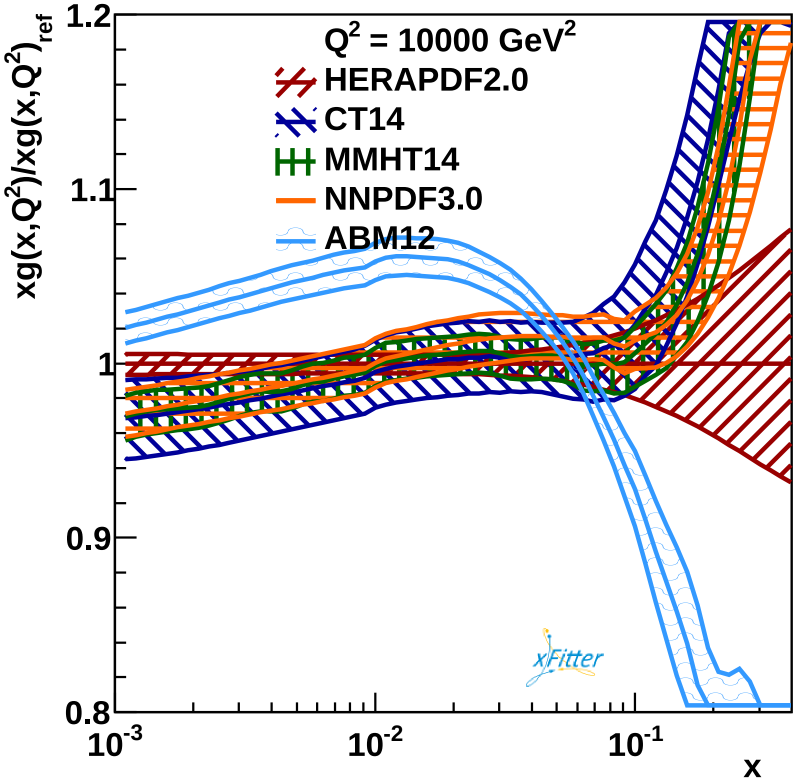
Higgs cross-section now and with 3 ab^{-1}





- Higgs fiducial cross section is determined for $\sqrt{s}$ = 13 TeV with 20% (30%) accuracy for $H \to 4\ell$ ($H \to \gamma\gamma$) channel using 14.8 fb^{-1} (13.3 fb^{-1}) by ATLAS.
- $H \to 4\ell$ channel is not much senstive to background/pileup effects, for 14 TeV 3 ab^{-1} luminosity one may expect uncertainty of $\sim$ 1.5% per experiment or 1% for the combination (excluding luminosity uncertainty).
- Theoretical uncertainty from PDFs, dominated by the gluon density uncertainty is at 2% level. Similar error from α_S

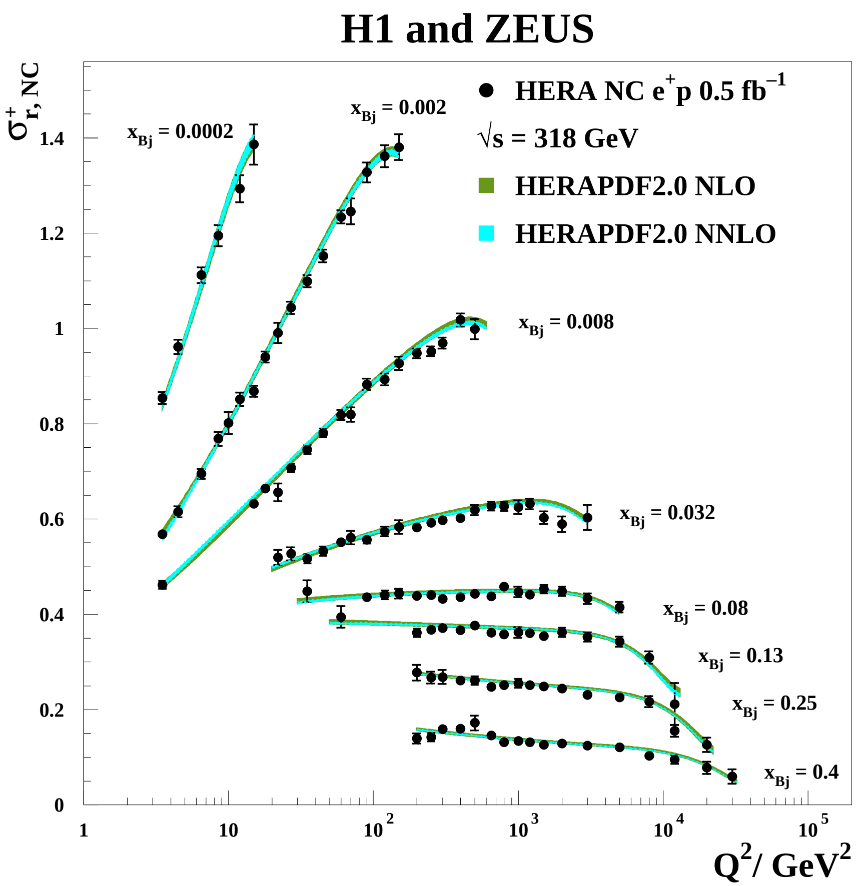
The gluon distribution from the 5 PDF sets



- Gluon at $x \sim 0.01$ important for Higgs production
- Gluon at $x > 0.3$ important for searches
- Gluon at $x \sim 0.1$ important for $t\bar{t}$ production.

- Good agreement of the three PDF4LHC sets (MMHT14, CT14 and NNPDF3.0)
- ABM12 set has different (low) α_S, differs the most.
- HERAPDF agrees with PDF4LHC for $0.01 < x < 0.1$, lower at high x and higher at low x.

HERA data for the gluon distribution



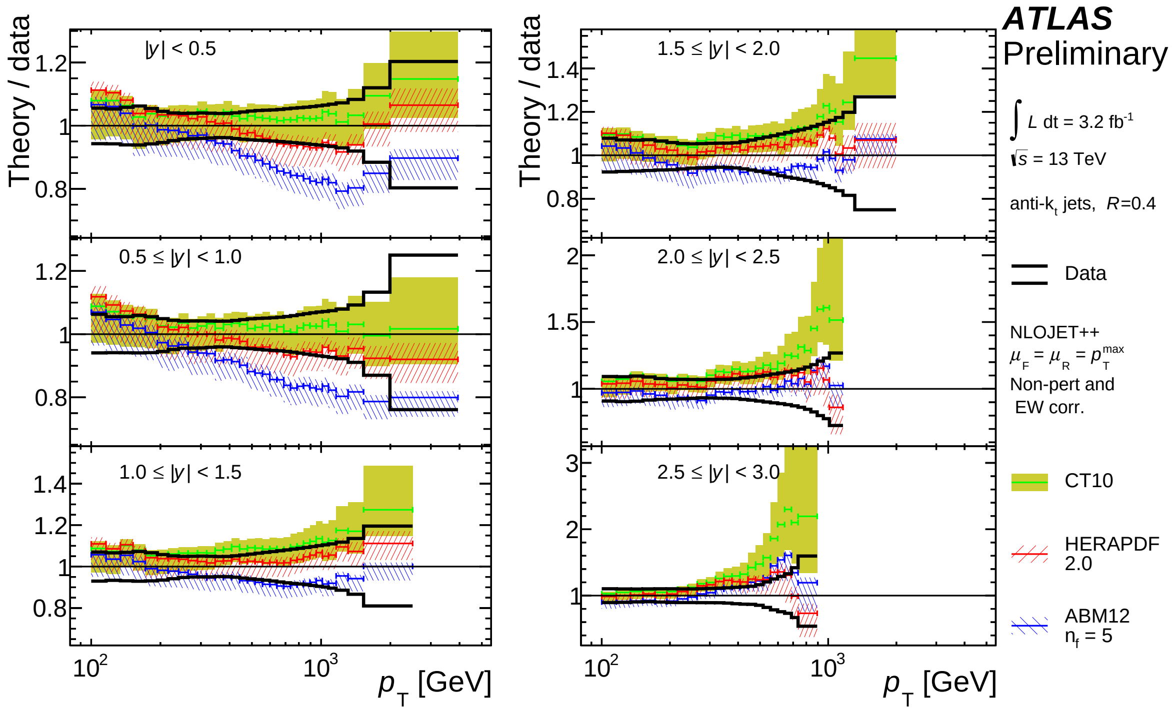
- Observable:
  $\sigma_r \approx F_2 - \frac{y^2}{1+(1-y)^2} F_L$
  where $0 < y \leq 1$ and
  $S\,xy = Q^2$.
- Constraints on $xg(x, Q^2)$ from scaling violation of the SF F_2:

$$\frac{dF_2}{d\log Q^2} \sim \alpha_S\, g$$

- Measurement of F_L at HERA is of limited accuracy.

- The Q^2 dependence of F_2 is well constraint by the data, leading to experimentally precise determination
- Some tensions between data and theory with NLO (NNLO) fit χ^2/N_{DF} = 1357/1131 (1363/1131). → N³LO ?

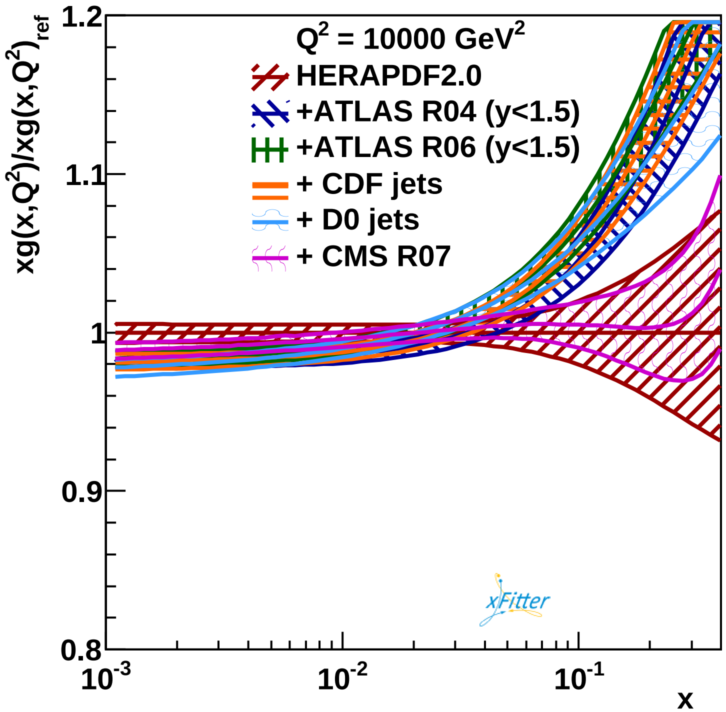
Inclusive jets at $\sqrt{s} = 13$ TeV

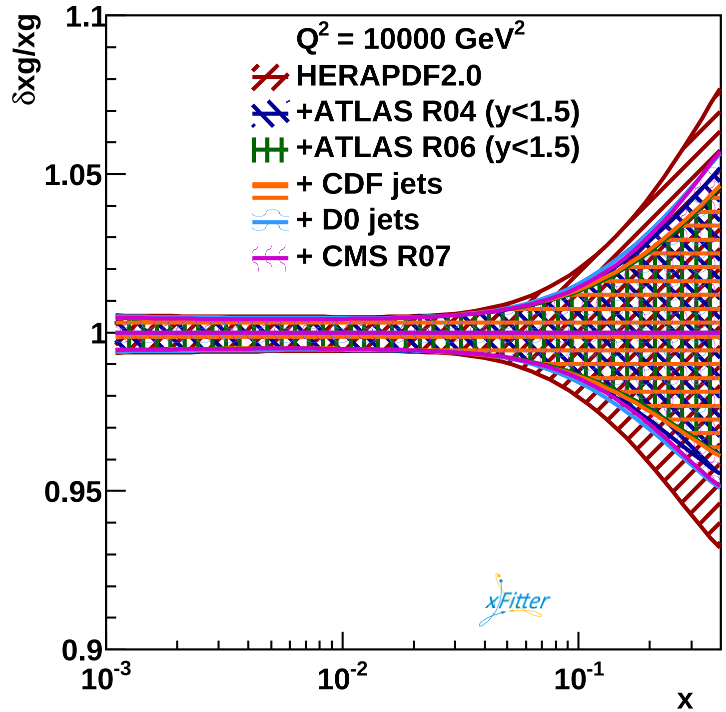


- New measurement of inclusive jet cross section using $\sqrt{s} = 13$ TeV data
- The dominant uncertainty, due to JES, is at 5% level for $|y| < 0.5$ and $p_T < 1$ TeV.
- Compared to predictions using NLOJET++ plus EWK corrections to modern PDF sets.

ATLAS-CONF-2016-092

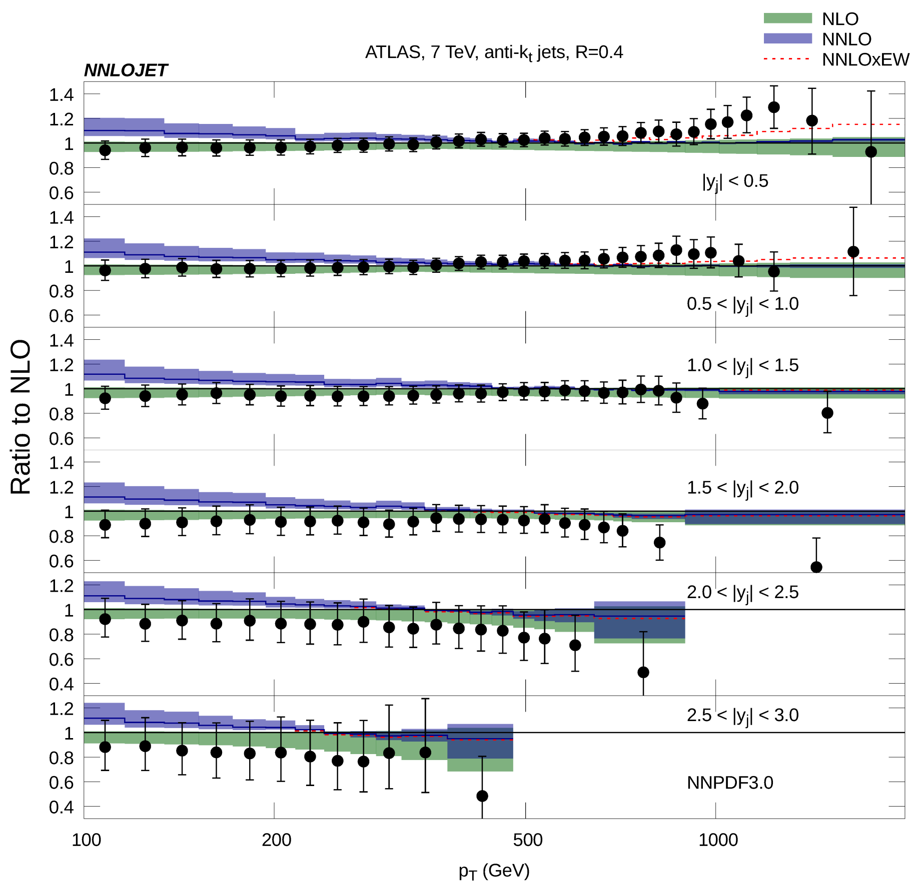
Impact of jet measurements on xg





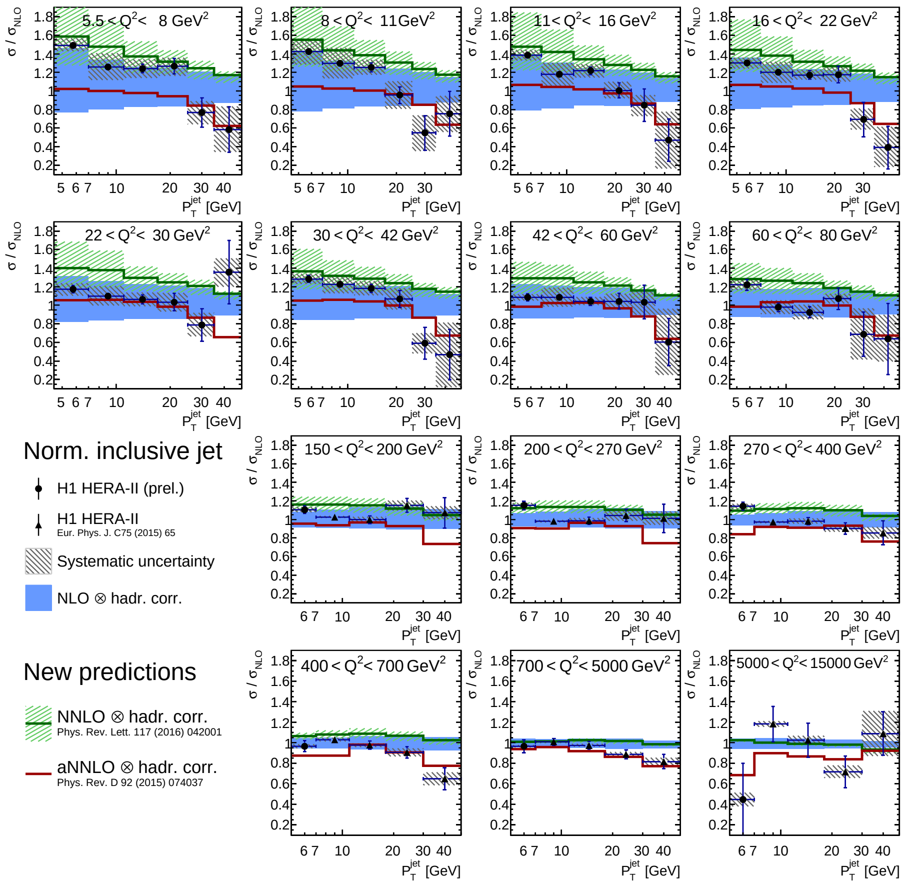
- Use PDF-profiling method to estimate impact of the jet data on HERAPDF2.0.
- Try different jet data: run-II DO PRL101:062001, CDF PRD78:052006, CMS at $\sqrt{s} = 7$ TeV ($R = 0.7$), Phys. Rev. D87 112002.
- All jet samples have comparable constraining power on gluon.
- D0,CDF and ATLAS $R = 0.4, 0.6$ jet measurements lead to harder gluon, CMS data do not change the shape significantly.

NNLO calculations for jets



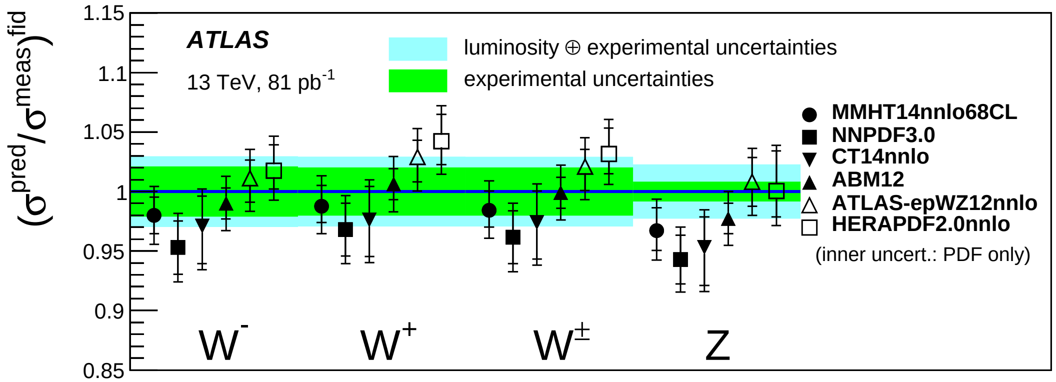
Very recently, NNLO predictions for inclusive jet production became available (arXiv 1611.01460). The correction is relatively large at low p_T, the impact is to be evaluated.

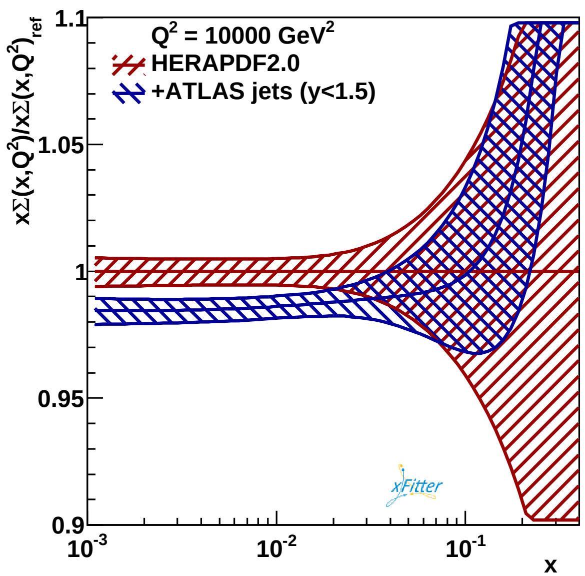
NNLO predictions vs DIS jet data



- Normalized to inclusive DIS, inclusive-jet and dijet measurements using H1 HERA Run-II data compared to approximate NNLO prediction from JetViP and NNLO from NNLOJET (H1prelim-16-062).
- NNLO improves description of the data.

W, Z production at $\sqrt{s} = 13$ TeV

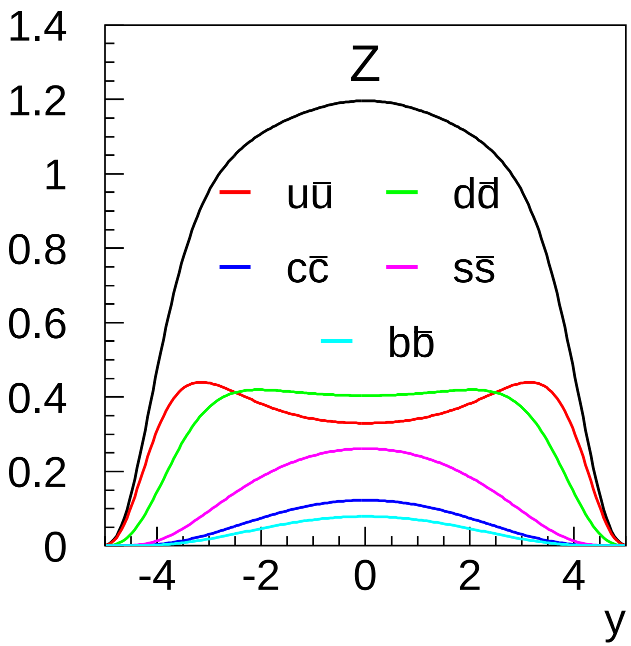


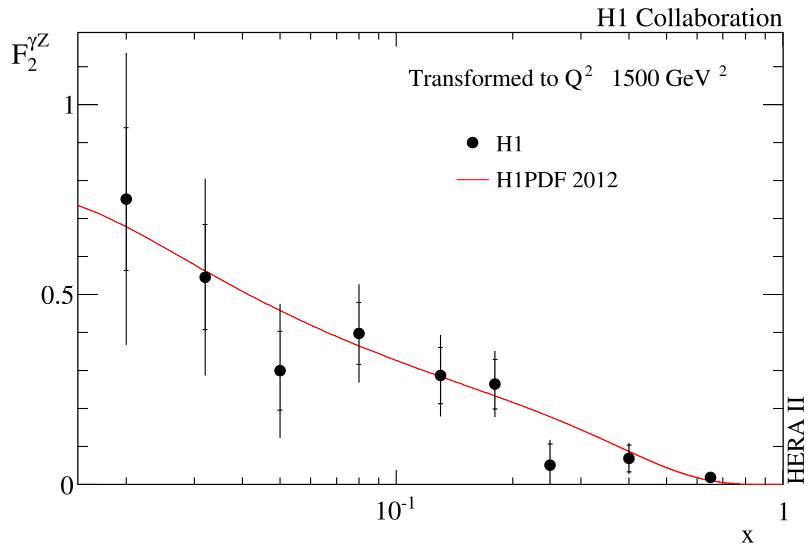


$\rightarrow$ need for better σ_Z prediction.

- Even for early $\sqrt{s} = 13$ TeV data the dominant uncertainty on the fiducial Z-boson production cross section comes from the luminosity.
- The luminosity uncertainty is improved for $\sqrt{s} = 8$ TeV data to 1.9%. For $\sqrt{s} = 13$ TeV data it is now at 2.1% and 1.8% for $\sqrt{s} = 7$ TeV data.
- The difference between HERA vs PDF4LHC pdfs may be explained by the pull of the jet data.
- If the theory predictions are understood, Z production can serve as a very good luminosity monitor.

Towards accurate predictions of σ_Z

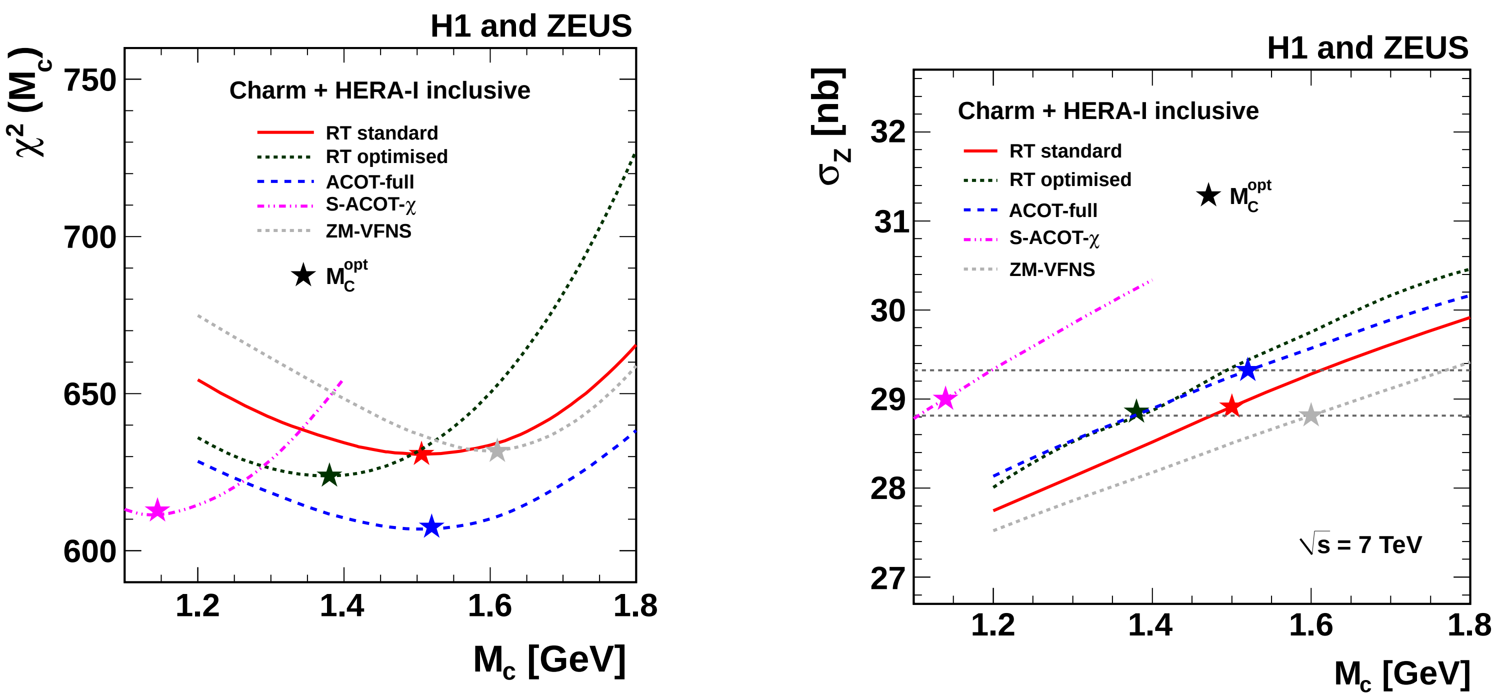




$$\tilde{F}_2^{\pm} \approx F_2 - (v_e \pm P_e a_e)\kappa \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z}$$

Accurate predictions require few permile σ_r measurement. In addition, flavour decomposition must be controlled (γ has different couplings to quarks vs Z) using e.g. $F_2^{\gamma Z}$. This requires large statistics samples with lepton beam polarisation.

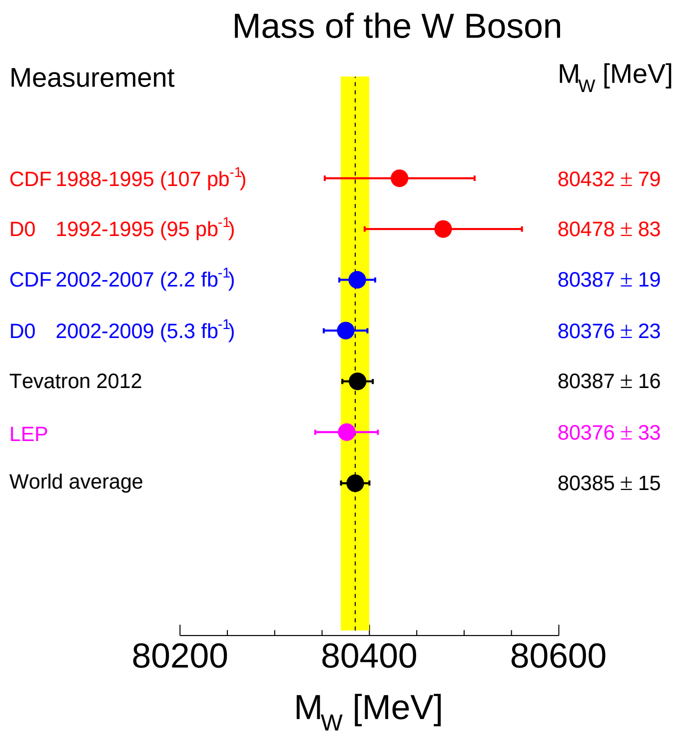
Constraining the charm-quark distribution

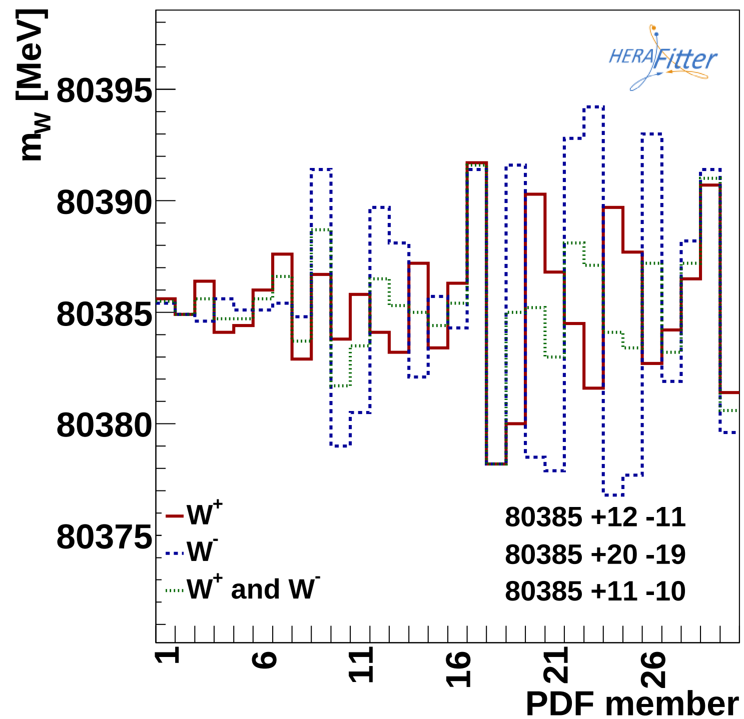


- Charm-quark distribution can be computed perturbatively from the gluon density. The computation is however difficult and in many cases it is preferred to treat charm as a regular sea-quark ("VFNS").
- Several VFNS exist, they may differ significantly.
- Fitting different schemes to the HERA F_2^{cc} data constrains the schemes; as the result predictions for the LHC become more stable.

H1+ZEUS: Eur.Phys.J.C73 (2013) 2311

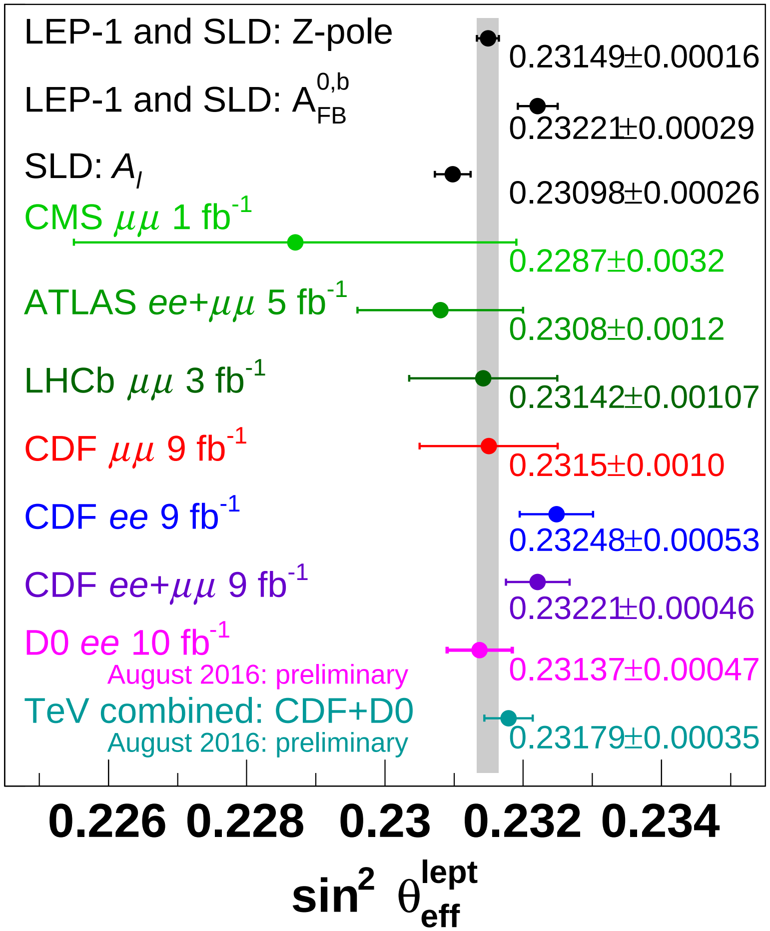
Measurement of W-boson mass





Experimental precision on M_W from Tevatron surpasses LEP. LHC can aim for < 10 MeV experimental uncertainties. PDF errors however are at > 10 MeV level, driven mostly by uncertainties of valence quarks at $x \sim 0.01$ (W-polarisation) and second generation production, $c\bar{s} \to W$ (W p_T). While difficult with high pileup, the measurement should be reported such that updates in PDFs could be used to update determination of m_W.

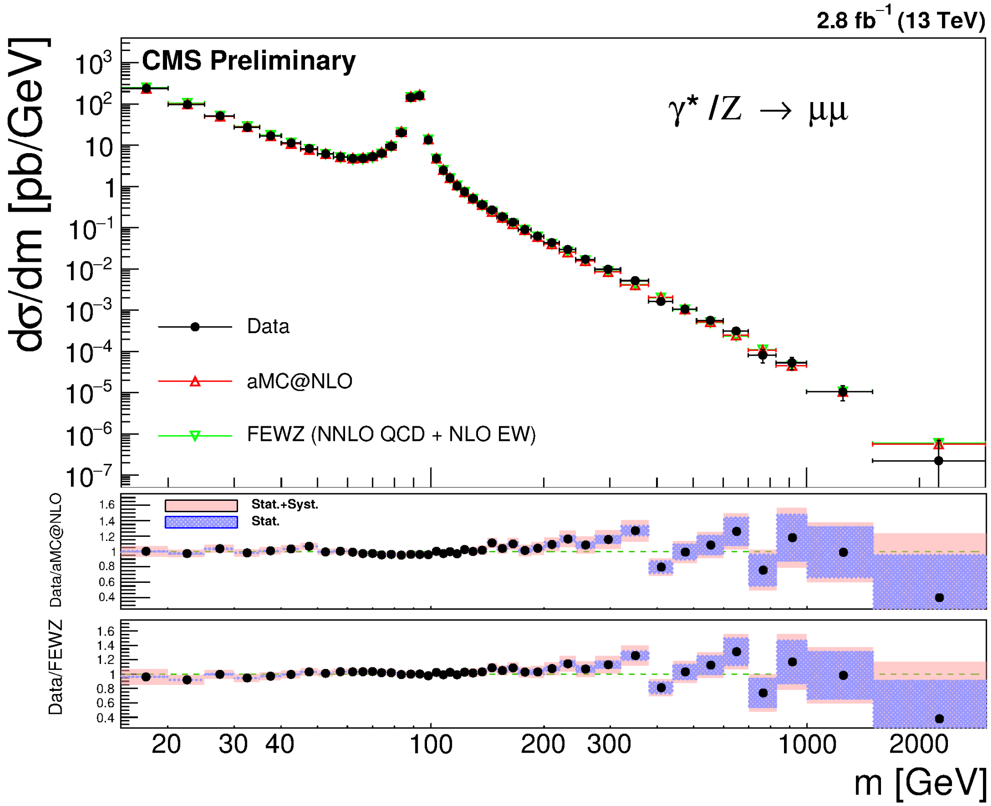
Measurement of $\sin^2\theta_W$



- Measurements of $\sin^2\theta_W$ at Tevatron approach LEP/SLD accuracy.
- Despite much larger Z samples, the measurements at the LHC are not competitive at the moment due to dilution in Z polarisation and associated uncertainties.
- Dominant PDF uncertainties are due to u_v, d_v at $x \sim 0.01$ and sea to valence quark ratio (similar to M_W). They can be controlled to some extend by measuring FBA off M_Z-peak and using W charge asymmetry. Uncertainties should decrease with more luminosity.

$\rightarrow$ input from DIS to control valence and sea quarks at intermediate $x \sim 0.01$.

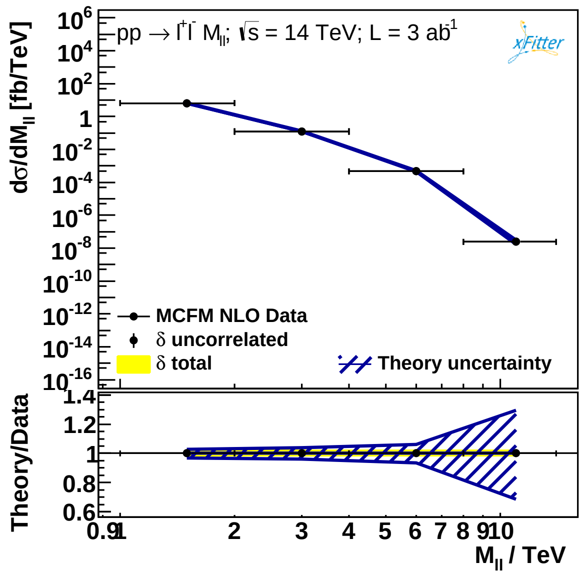
Inclusive Z/γ^* production as $\sqrt{s} = 13$ TeV

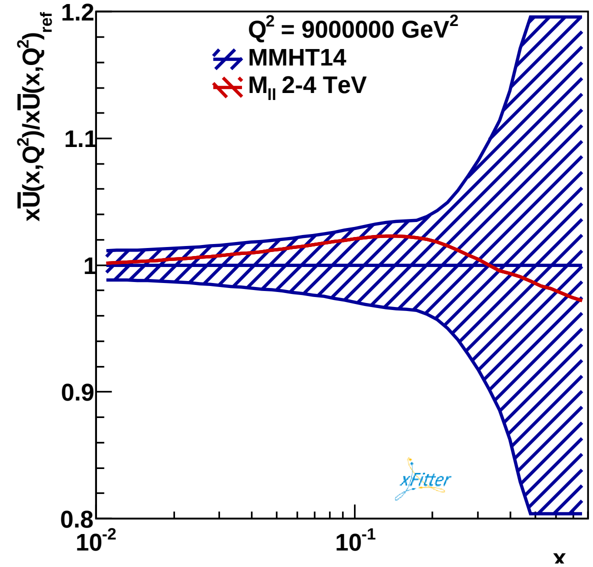


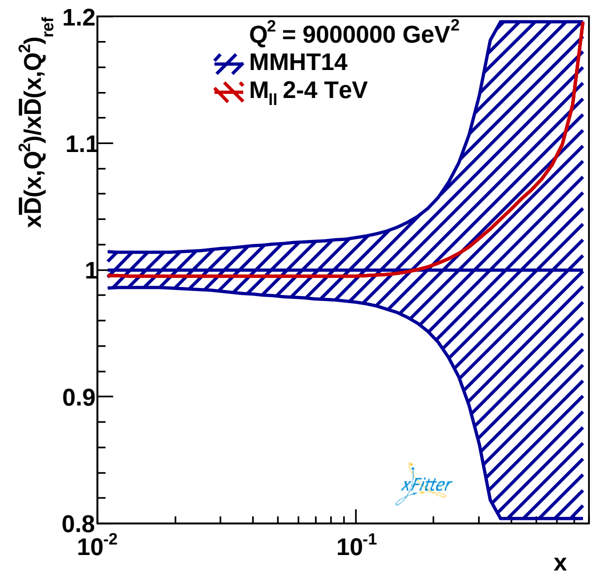
- Measurement of $d\sigma/dM_{\mu\mu}$ in $15 < M_{\mu\mu} < 3000$ GeV range, with $\sim 2\%$ systematic uncertainties for the peak region (plus 2.7% lumi).
- Agrees well with NLO and NNLO expectations.

CMS-PAS-SMP-16-009

High mass DY with 3 ab^{-1}

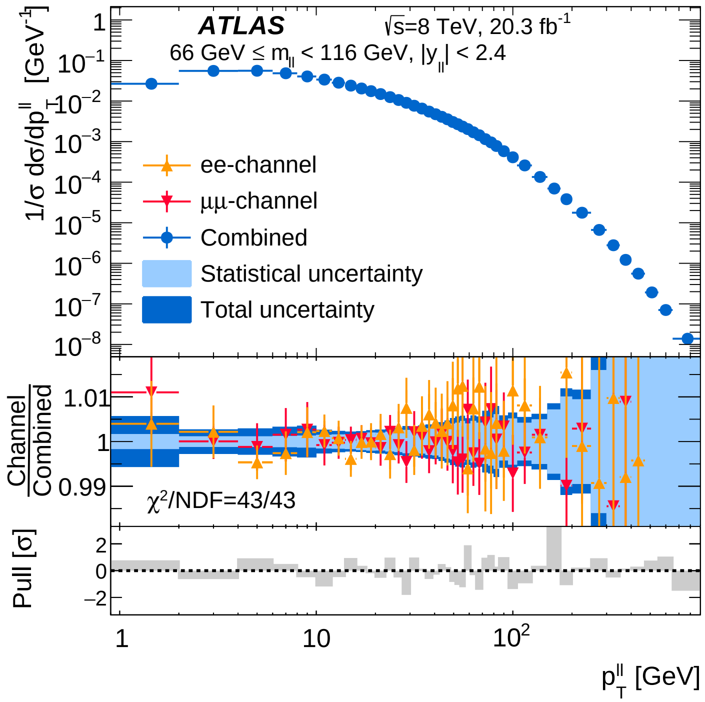


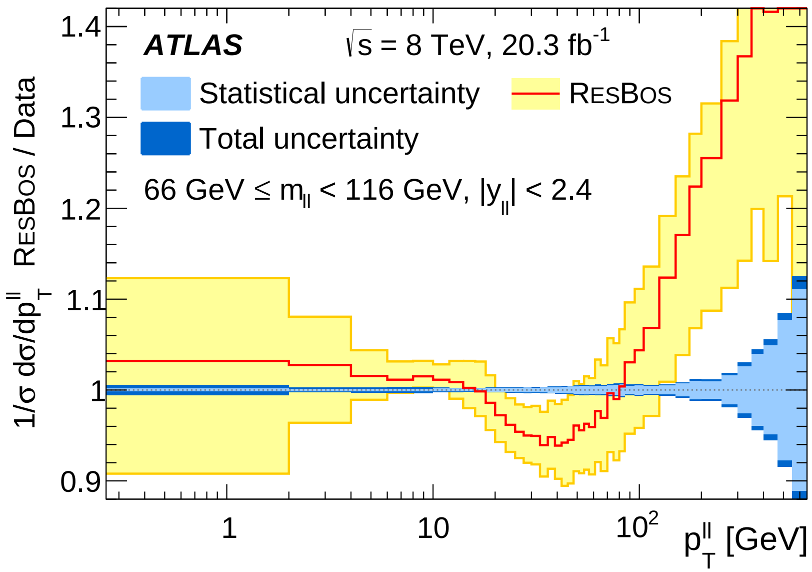




- Last accurately measurable bin is at $2 < M_{\ell\ell} < 4$ TeV. Use PDF re-diagonalization procedure (Phys.Rev.D80:014019) to determine the linear combination of PDFs affecting this bin the most.
- Largest sensitivity to $\bar{U} = \bar{u}$, small to $\bar{D} = \bar{d} + \bar{s}$.

Measurement of Z_{p_T}

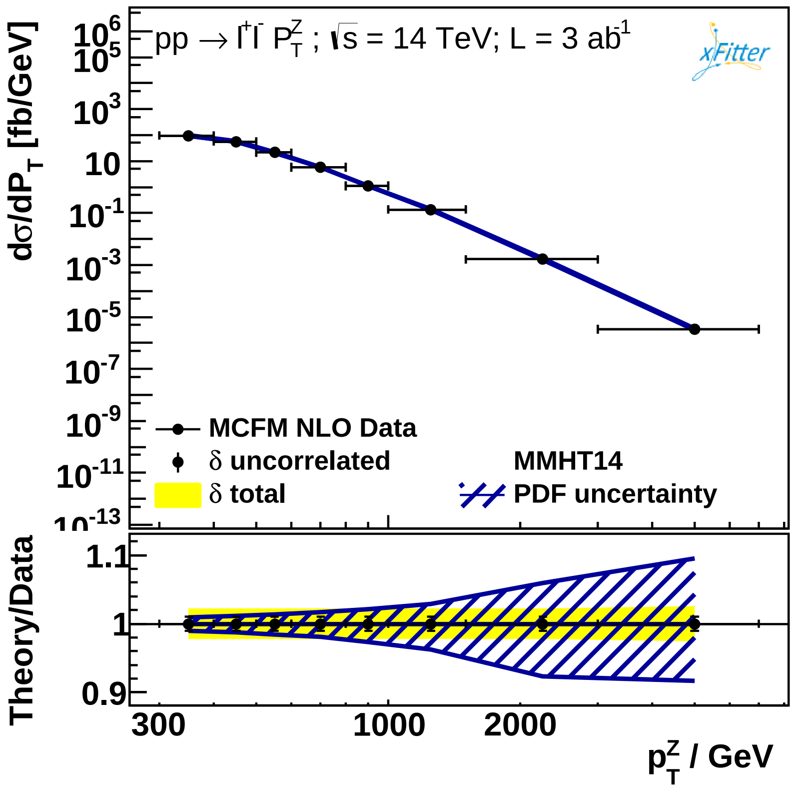


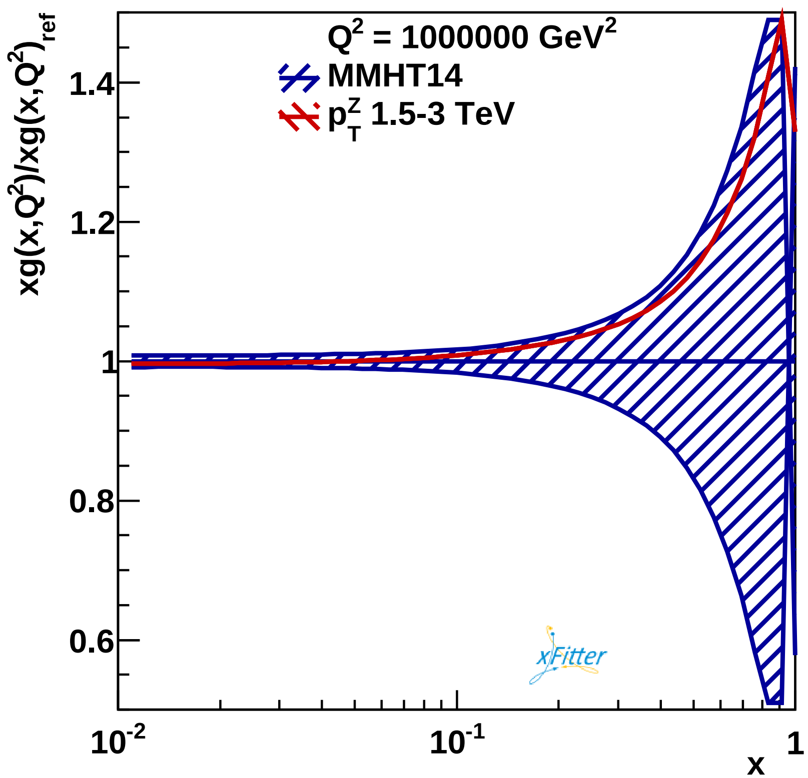


- Several measurements of Z_{p_T} at $\sqrt{s} = 7$ and 8 TeV by ATLAS and CMS.
- ATLAS measurements use both $Z \to ee$ and $Z \to \mu\mu$ channels, which have comparable accuracy. The combined result is accurate to better than 0.5% for $P_T < 100$ GeV range.

ATLAS, arXiv:1512.02192

p_T^Z with 3 ab^{-1}





Accurate (better than 1%) measurment of Z_{p_T} up to $1.5 < p_T < 3$ TeV bin where PDF errors are at $\sim 5\%$ level. Process sensitive to (N)NLO and EWK corrections, potentially new physics effects.

$\rightarrow$ largest sensitivity to $xg(x)$ at $x \sim 0.3$.

Summary

- A number of precision measurements at the LHC will challenge theoretical predictions.
- PDF uncertainties can be significantly reduced by a future ep collider, provided large kinematic coverage, ccntrol of efficiencies and luminosity at $\sim 0.1\%$ level.
- It is important to have multiple ways to control PDFs, e.g. gluon density should be measured using scaling violation, F_L and DIS-jets.
- Sea decomposition, separation of valence/sea quark contributions is important for LHC predictions, e-beam polarisation, ability to measure CC, heavy flavour tagging are essential ingredients for the future collider.